

U.S. Department of the Interior
U.S. Geological Survey

Techniques for Assessing Sand and Gravel Resources in Glaciofluvial Deposits—An Example Using the Surficial Geologic Map of the Loudon Quadrangle, Merrimack and Belknap Counties, New Hampshire

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1627

Prepared in cooperation with the New Hampshire
Department of Environmental Services

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By David M. Sutphin, Lawrence J. Drew, Brian K. Fowler, and Richard Goldsmith
with the surficial geologic map by Richard Goldsmith and David M. Sutphin

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A method for estimating sand and gravel resources in
glaciofluvial systems based on surficial mapping techniques
and a geographic information system (GIS)

U.S. DEPARTMENT OF THE INTERIOR
GALE A. NORTON, Secretary

U.S. GEOLOGICAL SURVEY
CHARLES G. GROAT, Director

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METRIC CONVERSION FACTORS

Multiply	By	To Obtain
inch (in)	25.4	millimeter
foot (ft)	0.3048	meter
yard (yd)	0.9144	meter
square yard (yd ²)	0.8361	square meter
cubic yard (yd ³)	0.7646	cubic meter
mile (mi)	1.609	kilometer
square mile (mi ²)	2.590	square kilometer
millimeter (mm)	0.03937	inch
meter (m)	3.281	foot
meter (m)	1.094	yard
square meter (m ²)	1.196	square yard
cubic meter (m ³)	1.308	cubic yard
kilometer (km)	0.6214	mile
square kilometer (km ²)	0.3861	square mile

Techniques for Assessing Sand and Gravel Resources in Glaciofluvial Deposits—An Example Using the Surficial Geologic Map of the Loudon Quadrangle, Merrimack and Belknap Counties, New Hampshire

By David M. Sutphin,¹ Lawrence J. Drew,¹ Brian K. Fowler,² and Richard Goldsmith³

ABSTRACT

A method for estimating the sand and gravel resources in glaciofluvial systems has been developed based on surficial mapping techniques that use the morphosequence concept and geographic information systems (GIS). Two different strategies are used to estimate gravel resources. One strategy estimates the sand and gravel resources contained in esker deposits; the other, which is more dependent on GIS, estimates resources in non-esker deposits. An attempt has been made to determine which deposits are sterilized; that is, those beneath the water table, adjacent to streams or roads, or encroached on by urbanization. Preliminary estimates using these methods indicate that about 158,000,000 m³ (206,000,000 yd³) of sand and gravel are present in the Soucook River valley part of the Loudon, N.H., 7.5-minute quadrangle. About 64,500,000 m³ (84,400,000 yd³) of these materials are in deposits above the water table. About 26 percent of the sand and gravel resources above the water table are unlikely to be mined because they have been sterilized. Of the remaining resources, 479,000 m³ (627,000 yd³) of gravel and 1,120,000 m³ (1,460,000 yd³) of sand are in esker deposits, and 9,400,000 m³ (12,300,000 yd³) of gravel and 38,300,000 m³ (50,100,000 yd³) of sand are in stratified non-esker deposits. With the addition of new well data, newer and more accurate estimates are possible.

INTRODUCTION

The purpose of this paper is to describe an objective method to estimate the volume and spatial occurrence of the coarse-grained fraction (gravels) produced by a glaciofluvial system and to identify the remaining sand and gravel resources in a test study area by categories of availability. The study area is the Soucook River valley in the Loudon, N.H., 7.5-minute quadrangle (fig. 1). The most obvious of the resources previously have been extracted and other resources may be located on lands designated for other uses. This method combines two modern analytical techniques—surficial mapping based on the morphosequence concept (Koteff and Pessl, 1981) and geographic information systems (GIS)—for a predictive tool that can be used to improve resource estimates of the sand and gravel fractions. The basic methodology is transferable to any region where glacial effluent was pumped by eskers or directed by ice channelways into the fluvial-lacustrine environment. This information will give local and regional planners a tool to estimate the impact of land-use decisions on nearby sources of sand and gravel.

THE PROBLEM

The most important commercial sources of sand and gravel in the United States are river channels and glaciated terrain (Yeend, 1973). Fortunately, the State of New Hampshire has abundant sand and gravel resources left behind as the last Wisconsin glaciers retreated. Larger rivers, such as the Connecticut and Merrimack, and lesser ones, such as the Soucook, have sand and gravel resources associated with them. Gravel (defined as 38 mm and larger)

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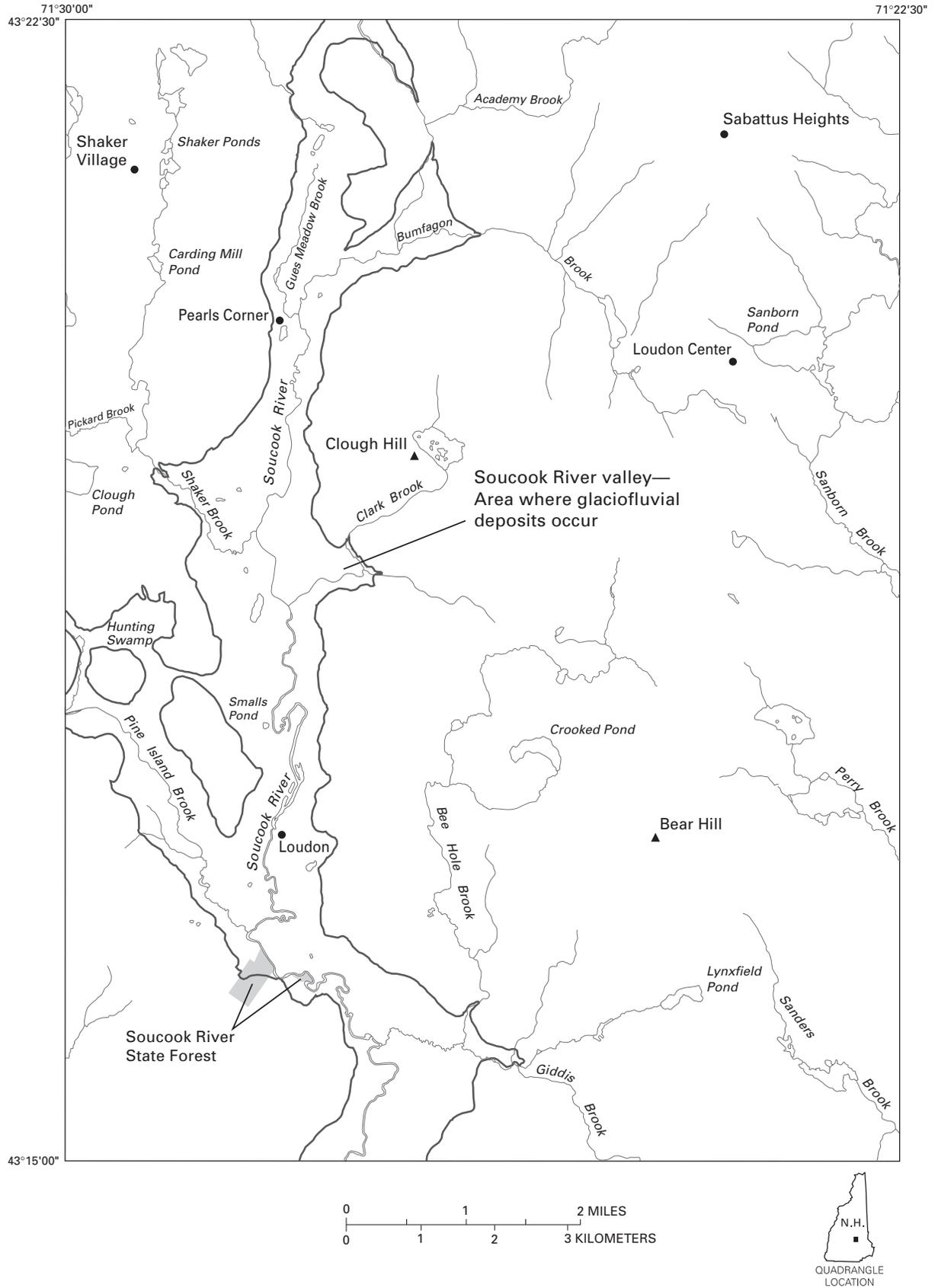


Figure 1. Map showing the location of the Soucook River valley in the Loudon, N.H., quadrangle.

is the more prized commodity in a sand and gravel deposit. Gravel most commonly is used as aggregate in concrete, as road-base material, and as fill. When gravel is found, sand often occurs as the more abundant, but much less valued, fraction.

For more than 30 years, however, a major problem facing the aggregate industry has been the land-use conflict, whereby land containing potentially rich sand and gravel resources is more valuable for building development, recreation, or environmental uses (Yeend, 1973; McDivitt and Manners, 1974; Barton, 1982). In such instances, sand and gravel resources are said to be sterilized, or removed from future production, because they are on land set aside for another purpose.

Sterilized deposits are those deposits that, for various reasons, are not mined. The term "sterile" is used in the coal mining industry to define coal seams that are not mined (Thrush, 1968). In the case of the glaciofluvial gravel deposits in the Loudon quadrangle, the term is applied to deposits that, for reasons of availability, are not mined and are not going to be mined soon. This may be because (1) they are overlain by, or are within 50 ft of, a highway that cannot be disrupted; (2) protected streams or wetlands run through them or are within 75 ft; (3) the gravel-bearing sedimentary units may be close to or beneath the local water table; or (4) they may be within a residential or business area where the landowners do not want a gravel pit or the noise, dust, and traffic that a nearby gravel pit may produce.

Transportation costs and land-use conflicts are two major factors that may contribute to future shortages of gravel to fill the aggregate needs of modern society. Transportation costs for high-volume, low-cost commodities, such as sand and gravel, become prohibitive as hauling distance increases. To reduce costs, sand and gravel are produced near the point of use. As a result, the sand and gravel industry is usually concentrated in large, rapidly expanding urban or suburban areas or where highways, dams, and other large-scale projects are under construction.

People move to the suburbs to escape the noise and discomforts of city life, so they often oppose pits and quarries in their midst with the noise and dust, pits left in the ground after the recoverable material has been removed, and the possibility of danger for children. The conflict has become so intense in the Denver, Colo., area that there are shortages of sand and gravel despite once having vast resources. There, availability of sand and gravel resources declined because of adverse zoning, noncompliance of existing mining operations with existing regulations, increased demand, inadequate grain size to meet specifications, and environmental and visual concerns (Langer, 1998).

Declining sand and gravel resources lead to additional problems. For instance, if the rate at which these resources are restricted from development continues unabated, available resources will be depleted. To create a sufficient supply of aggregate, industry will turn to crushed rock as a substi-

tute for sand and gravel. This would require drilling and blasting of hard rock, which are unpopular in urban areas and raise the cost of production.

As the population becomes more suburban, land-use problems are beginning to arise in New Hampshire and in the Soucook River valley in particular. Sand and gravel resources should be assessed to assure that the most is made of them, so that the quantity and quality of the resources being sterilized is known and considered in land-use decisions.

Existing techniques (Dunn, 1991) for assessing gravel resources in glaciofluvial deposits are imprecise because they are based on the overall areal distribution and assumed thickness of these deposits, and therefore overestimate contained gravel resources. Furthermore, existing techniques do not account for the spatial distribution of the resource, previous extraction, or loss from incompatible land use (housing, roads, golf courses, and other uses) or land-use classifications (parks and wetlands).

THE IMPROVED METHOD⁴

The improved volumetric method for estimating the sand and gravel resources in the glaciofluvial setting is inexpensive, quick, and accurate. Digital information from the Internet is increasingly available to the public. Access to such information, rapidly declining computer hardware costs, and the availability of software have made GIS's affordable to an increasingly wider audience.

The method consists of two phases: data collection and analysis. In the data collection phase, a GIS of the Loudon quadrangle was developed from hand-digitized information and information from other sources, such as state and federal Internet sites. In the analysis phase, the GIS was used to calculate the volumes of sand and gravel resources in the Loudon quadrangle in both esker and non-esker deposits.

DATA COLLECTION

In its most general form, a GIS is the hardware, software, and geographic data designed to manipulate, analyze, and display all forms of registered geographic information. A GIS is more than a simple computer system for producing maps, although it can create maps at different scales, in different projections, and in different colors; it is an analytical tool used to reply to spatial queries. Each feature with-

⁴The lattice for the geographic information system (GIS) used 10 m × 10 m cells; therefore, all areal measurements are in square meters (m²). Volumes of sand and gravel resources were calculated using the same lattice and are given in cubic meters (m³) with equivalents in cubic yards (yd³) provided for convenience. Some measurements that are dependent on the 1:24,000-scale base map of the Loudon 7.5-minute quadrangle (for example, unit thicknesses and well depths) are given in feet.

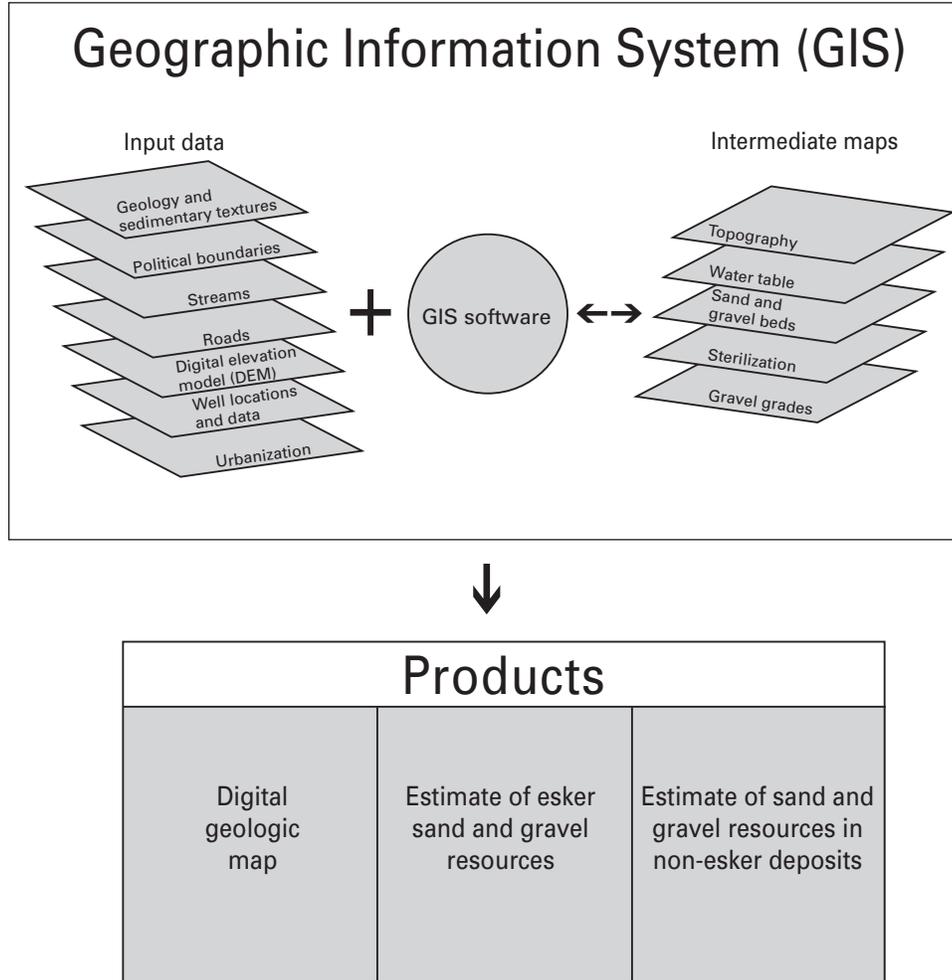


Figure 2. Diagram showing the different data sets that go into making the GIS, intermediate maps, and products.

in a GIS, be it a point, line, or polygon, is attributed with data that describes it. Spatial relationships between map features can be identified, and different data sets are linked so that analysis can be performed among them. Figure 2 shows the source data, the data sets that were assembled for the GIS, and the products (analyses) that were produced.

TOPOGRAPHY

A digital raster graphics (DRG) map of the Loudon quadrangle was purchased from the USGS as was a mylar separate of the 20-ft topographic contours used on the published maps of the quadrangle. The DRG is basically a georeferenced digital image of the published paper 1:24,000-scale map. It is used to underlay the digital data. The topographic contours on the mylar were scanned and converted to a line coverage. The contours are used as a topographic base for the geologic map (plate 1).

GROUND WATER

This study also relies on elevations from the water-well completion records (New Hampshire Department of Environmental Services (NHDES), written commun., 1999). In the Loudon quadrangle, as in much of New England, the topography and the water table may be very close to one another in elevation with streams, lakes, swamps, and bogs adjacent to low, gravel-bearing hills and terraces. Therefore, errors in elevation between the water-table surface, the bottom of the sand and gravel beds, and the topography have a large influence on the estimated amount of gravel resources. For the calculated water-table surface to be properly below the topographic surface, it was necessary to set a minimum thickness for the stratified deposits in the valley at 2 ft.

Dorian and Zwartendyk (1984) discuss the strengths and weaknesses of volumetric estimations such as this. They summarize that these estimates are relatively simple to

do, require a minimum of data, and are excellent for deposits with simple and uniform geometry. The weaknesses of volumetric estimates are (1) that if there is paucity of data, it is not apparent to the uninitiated; (2) a geologic similarity between areas is assumed; and (3) that volumetric estimates may be misused. The estimates put forth here would be more accurate if there were a greater number of water wells in strategic locations as well as a refinement of GIS software, data bases, and techniques.

ROADS AND STREAMS

Digital line graphics (DLG) maps of the streams and roads at a scale of 1:24,000 were downloaded from the U.S. Geological Survey (USGS) Web site (http://edcftp.cr.usgs.gov/pub/data/DLG/LARGE_SCALE/L/loudon_NH/. Accessed February 1999). GIS software was used to calculate the areas of polygons and to draw buffer areas on either side of the streams and roads to show where current restrictions do not allow quarrying of the gravel. The total area of the Soucook River valley in the Loudon quadrangle where gravel resources are expected to occur is 20,400,000 m².

For the roads, 50-ft-wide buffers represent areas where quarries cannot be located; stream buffers are 75-ft wide. In the Soucook River valley, the road buffers account for 1,930,000 m² (9.5 percent) of the area where gravel resources are expected to occur that cannot be mined for gravel under current restrictions. Streams on the map and their buffers account for 2,530,000 m² (12.4 percent) of the valley that are sterilized. The total land area made unavailable by streams and roads is less than the sum of the two areas because the buffers often overlap. Of course, not all of the buffered area is underlain by economic gravel deposits.

URBANIZED AREAS

The map showing urbanized areas includes additional areas that are not part of the stream- or road-buffer maps where new mining of sand and gravel may not occur. These areas include housing and business areas, State parks, campgrounds, the race track complex⁵, and pits where gravel previously was or currently is being removed. These are places where existing structures or ownership would make it too expensive and too difficult for a gravel-mining operation to get the rights to mine the underlying resources. Items on the urbanization map are classified based upon the relative economic cost of buying the land to quarry the underlying sand

⁵The race track complex, located north of Pearls Corner, was not well developed when this project began and was not considered to have sterilized the underlying resources.

Table 1. Summary of types of sterilization, by area, that affect sand and gravel resources in the Soucook River valley.

Sterilization type	Area ¹ (m ²)	Percent of of total area ²
Road buffer	1,930,000	9.5
Stream buffer	2,530,000	12.4
Urbanization	3,610,000	17.7
Total	6,970,000	34.2

¹Buffer totals are not additive because they overlap in many places.

²Total area where stratified glaciofluvial deposits have formed is 20,400,000 m².

and gravel. For example, a lower classification was given to relatively inexpensive housing on a large parcel. Expensive, more densely packed, housing on relatively small parcels of land received a higher classification. Clearly, given equal circumstances, a gravel company would be more likely to buy a large parcel having an inexpensive house on it than to buy several small parcels each having a large, expensive home. Businesses were of a higher classification than were residential areas. The urbanized parts of the Soucook River valley part of the Loudon quadrangle (including the quarries) cover 3,610,000 m² (17.7 percent) and often overlap with the road and stream buffers. Active, inactive, or abandoned gravel pits, where the sand and gravel resources have been removed or are being removed, account for 1,630,000 m² (almost 8.0 percent) of the surface.

The road and stream buffers and urbanization maps were used as masks to prevent the sand and gravel in sterilized areas from being counted as resources. The combined stream, road, and urbanization masks cover 6,970,000 m² (34.2 percent) of the Soucook River valley part of the Loudon quadrangle. About 14 percent of the total unavailable area in these three sterilization maps occurs in more than one map. That is, for about one-seventh of the area restricted from mining, more than one restriction applies. Estimates of these sterilized areas are shown in table 1.

GEOLOGY

An important part of this project was to digitize the new geologic map of the Loudon quadrangle. A draft of the geologic map was traced, scanned, and converted into a polygon coverage. Each polygon was attributed according to the geologic unit it represented. The textures of stratified deposits also became attributes in the data base.

The Loudon quadrangle was mapped using the morphosequence concept (Koteff, 1974; Koteff and Pessl, 1981). A morphosequence is a single sequence that specifically refers to a continuum of landforms composed of melt-water deposits, from more collapsed forms due to melting ice blocks at the head or upstream parts of outwash to less progressively collapsed forms downstream (fig. 3). In each

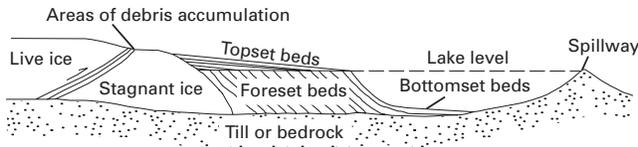


Figure 3. Diagrammatic profile of a lacustrine ice-contact morphosequence (after Koteff (1974, p. 128–129) and Koteff and Pessl (1981, p. 7)).

morphosequence, the texture at the surface of the deposits is generally coarser near the head of outwash and becomes finer grained downstream. Textural boundaries, however, are not always sharp or easily distinguished. Within a morphosequence, gravel may be found in an area that is predominantly sand or sand may be found in an area that is predominantly gravel. On the geologic map, each new morphosequence begins downstream from a retreatal position of the stagnant ice margin and is given a new informal geologic name and map-unit symbol.

ANALYSIS

In the analysis phase, the GIS was used as an analytical tool to identify spatial relationships between maps and, ultimately, to estimate the volumes of sand and gravel resources in glaciofluvial deposits in the Loudon quadrangle. GIS software was used to manipulate the geologic, geographic, and water-well completion data to (1) create representations of the topography, the top of the water table, the bottom of the sand and gravel resources, and the grades of the sand and gravel deposits; (2) to calculate the volumes of sand and gravel resources naturally endowed to the area; and (3) to calculate the amounts of those resources that may be sterilized.

Once the data were collected and entered into the GIS, two different analytical strategies were used to volumetrically estimate the glaciofluvial sand and gravel resources of the Soucook River valley part of the Loudon quadrangle. One strategy directly estimated the sand and gravel resources contained in esker deposits, and the other estimated those resources in non-esker stratified glaciofluvial deposits.

Estimation of the amount of sand and gravel in the eskers was done by identifying the eskers, calculating their areas using the digital geologic map, estimating thicknesses in several locations, and calculating their volumes from these values. Resources in eskers were calculated separately from other stratified glaciofluvial deposits because they are easily recognized on a topographic map and in the field and because industry uses a simple volumetric procedure to estimate their resources. The method used to estimate the sand and gravel resources in non-esker stratified glaciofluvial deposits, however, involved using the water-well completion

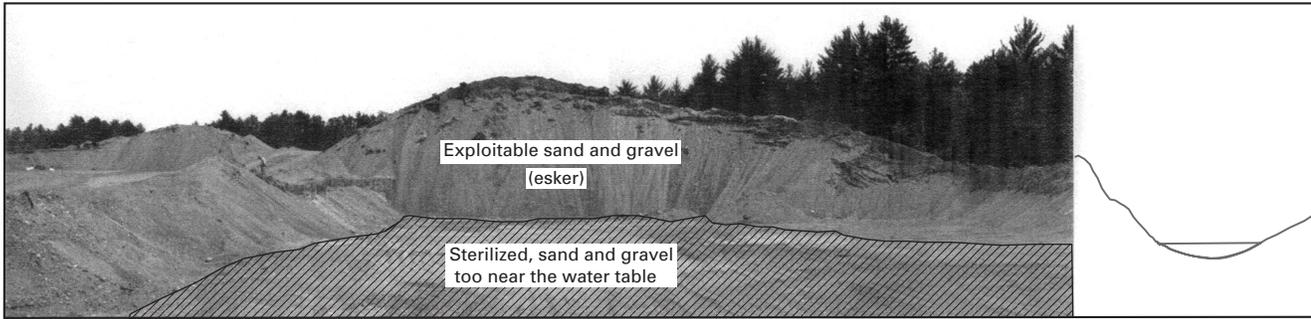
reports, the digital geologic map, and GIS software. Digital lattices were created representing the surfaces of the water table and the bottom of the sand and gravel deposits; the differences between these surfaces and the topography were calculated. The result of these calculations is the thickness of the sand and gravel deposits above the water table. The geologic map and the water-well-completion reports provided information for creating a lattice showing the percentage of gravel at any location in the valley. The gravel grades were multiplied by the thickness of the sand and gravel deposits to estimate the tonnages of sand and gravel in the valley. This method was more reliant on GIS than the method used to estimate the sand and gravel resources in the eskers.

ESKERS

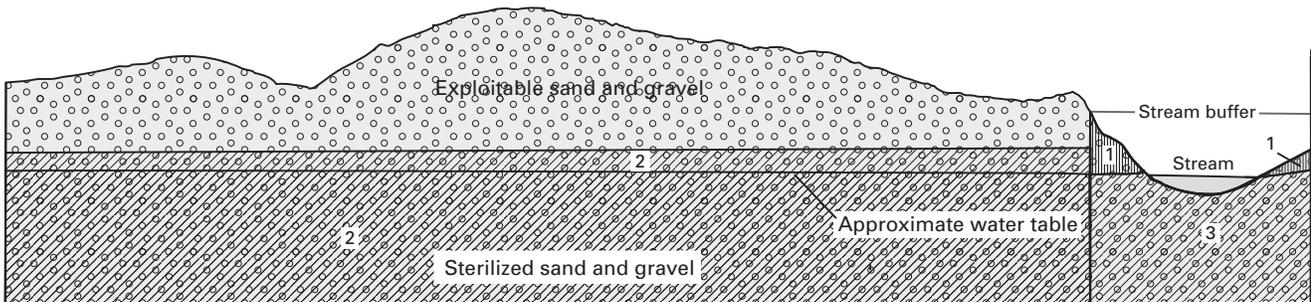
ESTIMATE OF SAND AND GRAVEL RESOURCES

Eskers are long, narrow ridges of coarse sand and gravel that were deposited in a tunnel in a receding glacier (figs. 4A, 4B). They formed in a high-energy glaciofluvial environment as meltwaters and rocks cascaded within the glacier pushed by a strong hydraulic head. At the foot of the glacier, huge boulders collided as they made their way out of the glacier. A jet of sediment-laden meltwater may have exited the foot of the glacier into a glacial lake forming the esker. Sediments in eskers may be quite coarse with the largest boulders weighing several tons. Eskers are the premier gravel deposits in glaciofluvial valleys like the Soucook River valley because they contain the greatest percentage of boulders and coarse gravels with lesser portions of sand. Eskers have sharp contacts when identified in the field; they can be recognized on a topographic map by their raised profile and closed contours and by a map pattern that resembles a string of raised oblong beads running down the glaciofluvial valley (fig. 5). Eskers are raised topographic features and are, therefore, attractive mining targets because much of the contained resources can be extracted without encroaching on the water table. They also are prized sites for residential construction because they afford views of the surrounding valley and adjacent hills; therefore, it is important to have estimates of the volume of gravel resources that are being sterilized by construction on eskers. Buried eskers, which can be an excellent source of gravel, are not obvious on the surface.

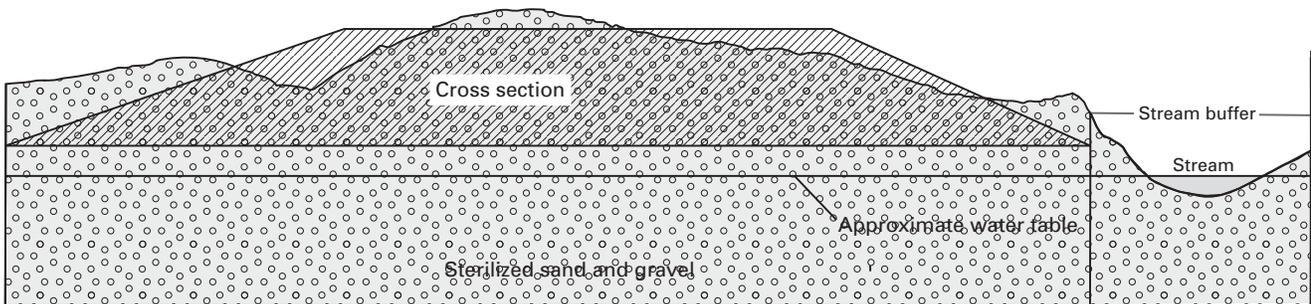
A trapezoidal cross section was used to estimate the volume of sand and gravel resources in eskers (fig. 4C). A trapezoid was chosen because the shape, which is broad at the base and narrower at the top, roughly approximates the cross section of an esker. This method is similar to that used in the aggregate industry, except that the GIS is used rather than on-site measurements. First, the area of the esker or any part of an esker was easily and accurately determined from GIS analysis of the digital geologic map. The widths



A



B



C

Figure 4. Illustrations showing the face of an esker being mined for sand and gravel. **A**, Photograph showing the location of exploitable sand and gravel and the surface below which mining is prohibited. **B**, Cross section of the same esker showing locations of the sterilized sand and gravel. Sand and gravel is sterilized if it

is (1) within 75 ft of a minor stream, (2) encroaching on or below the water table, or (3) within 75 ft of a minor stream and beneath the water table. Diagram is not to scale. **C**, Diagram of how the volume of an esker is estimated; not to scale.

of the base and shoulder of the esker and the thickness between the base and shoulder were estimated using the digital 20-ft topographic contours in the GIS. After the area of the trapezoidal cross section of the esker was determined, a mean thickness was calculated and multiplied by the area to derive the volume of the sand and gravel resources. To improve the accuracy of the estimates, the eskers were divided into several pieces to allow for their curves, bends, and other irregularities in shape. Esker material is commonly 30 percent boulders and coarse gravel and 70 percent sand, based on field observations; high-grade esker deposits

may be 40 percent boulders and coarse gravel.

Bliss (1998) developed a model for the volume of sand and gravel in eskers in Manitoba, Canada, from published data and determined that eskers contained a mean of 85,000 m³ of material. Ninety percent of the eskers modeled by Bliss (1998) had a volume of 12,000 m³ or more and 10 percent had a volume of 860,000 m³ or more. That is, 80 percent of the eskers in the model had volumes of between 12,000 m³ and 860,000 m³ (fig. 6). Bliss (1998) did not provide a descriptive model for the Manitoba esker deposits to compare those eskers with the ones in the Loudon quadrangle.

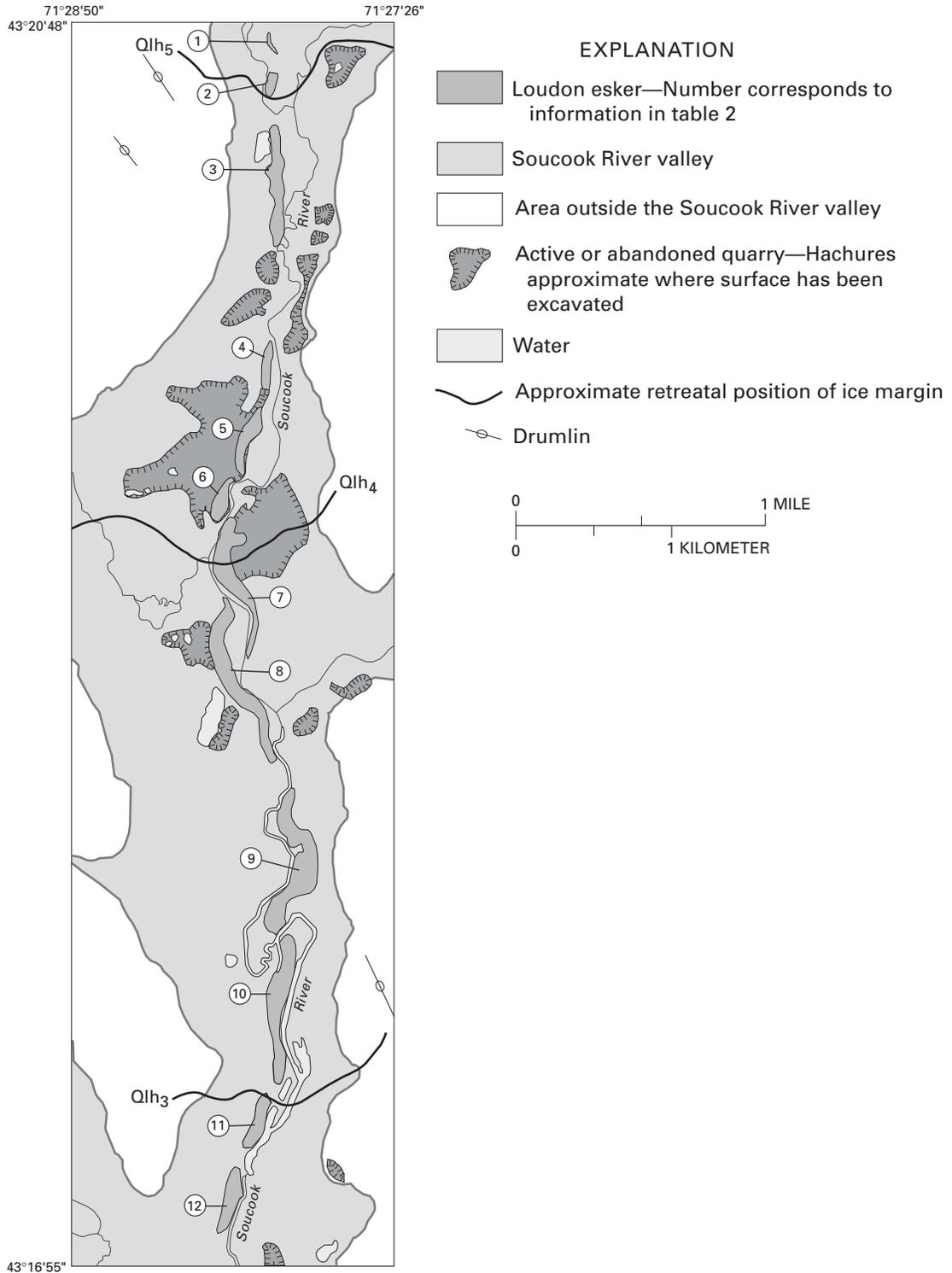


Figure 5. Geologic map showing known eskers in the Soucook River valley in the Loudon, N.H., quadrangle. Numbers refer to eskers listed in table 2.

After the volume of the esker's resources was determined, estimates were calculated for the amount of sterilized material by (1) determining the areas (in m²) of parts of eskers that had been sterilized, (2) estimating the thickness of the eskers in the sterilized parts, and (3) calculating the volume of the sterilized sand and gravel resources. By subtracting that volume from the total volume of the esker, the total exploitable sand and gravel resources were determined for each esker. These totals are shown in table 2.

SUMMARY OF ESKER SAND AND GRAVEL RESOURCES

There are 12 known eskers in the valley covering a total area of 370,000 m² (fig. 5). However, eskers 1, 5, and 6, have had their resources removed and are not included in this summary. Esker 9, the largest esker, covers 101,000 m², while esker 2, the smallest one, covers just 7,440 m². The mean area of the nine remaining eskers is 33,600 m². About 106,000 m² (or almost 29 percent) of these eskers occur within buffer areas for streams, roads, or urbanization, leaving 264,000 m² of the eskers available for exploitation. Undiscovered exploitable eskers, however, may occur buried beneath younger glaciofluvial sediments in the valley.

The known eskers in the river valley contain a total of about 2,140,000 m³ (2,800,000 yd³) of sand and gravel resources. The parts of the eskers sterilized by streams, roads, or urbanization contain about 546,000 m³ (714,000 yd³) (or over 25 percent) of sand and gravel resources. Approximately 1,600,000 m³ (2,090,000 yd³) (or almost 75 percent) of sand and gravel resources in the eskers remain available for possible exploitation. Esker 9 contains the most (625,000 m³, 817,000 yd³) sand and gravel resources, of which 54,300 m³ (71,000 yd³) (or less than 9 percent) is sterilized, leaving a total of 570,000 m³ (746,000 yd³) (over 91 percent) for possible exploitation. Esker 2 contains the least amount (17,300 m³, 22,600 yd³) of sand and gravel resources, of which 5,240 m³ (6,850 yd³) (more than 30 percent) is sterilized with the remaining 12,100 m³ (15,800 yd³) of sand and gravel resources available for possible mining. The mean volume of sand and gravel resources in the nine remaining eskers is 238,000 m³ (311,000 yd³) of which 60,700 m³ (79,400 yd³) (almost 26 percent) is sterilized.

Figure 6 shows the estimated volumes of the eskers in the Loudon quadrangle plotted using the esker volume model (Bliss, 1998). Only eskers 2 and 11 have volumes (table 2) less than the mean of 85,000 m³ (111,000 yd³) of the eskers in the model. The other eskers have volumes above the mean. The mean volume of eskers in the Loudon quadrangle is about 2.8 times the mean volume of the eskers in the model.

Table 2 also shows the estimated gross in-place values

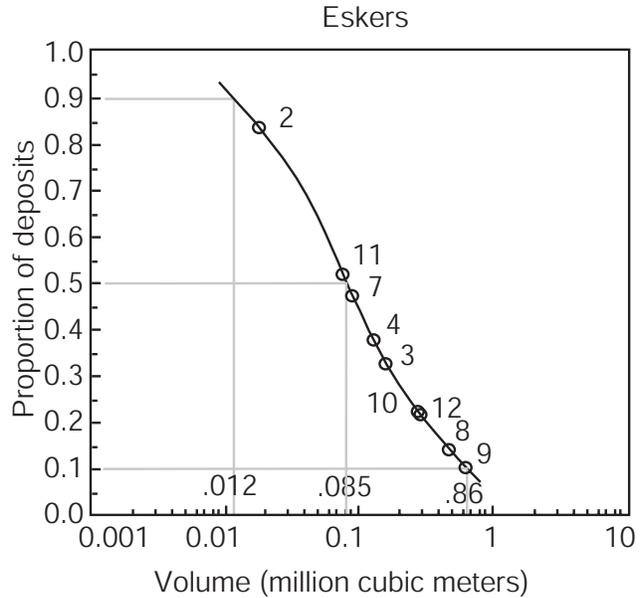


Figure 6. Graph showing esker volume model (Bliss, 1998). Eskers in the Loudon quadrangle are plotted as open circles. Numbers correspond to eskers listed in table 2. Eskers 1, 5, and 6 are not included because they already have been consumed.

of the sand and gravel resources at wholesale prices. The wholesale value is the in-place value of the sand and gravel prior to digging, screening, loading, and transporting. Gravel, with a wholesale value of \$0.75/short ton (st), is the primary target for development; sand, with a wholesale value of \$0.10/st, is a less prized but very abundant commodity. Examining the dollar values of esker sand and gravel resources makes it possible to judge the economic impact of the mining or sterilization of these resources in the Soucook River valley. These values, however, are for comparison only and may not reflect either prices in effect at the time of production, or economic factors involved in producing the resources. The amounts of sand and gravel in the valley and their values are not insignificant. If esker 9 were to be exploited fully while still regarding the limits of sterilization by roads, streams, or urbanization, it would produce approximately \$314,000 in sand and gravel, of which \$251,000 would come from gravel and \$62,800 from sand. Esker 2, in contrast, would produce \$6,670 in sand and gravel, of which \$5,340 would come from gravel resources, with the remaining \$1,330 from sand. The total in-place wholesale value of the nonsterile sand and gravel resources in eskers is \$881,000, of which \$706,000 would come from gravel and \$176,000 from sand. Assuming the 546,000 m³ (714,000 yd³) of sterilized sand and gravel contains 30 percent gravel, its value would amount to about \$301,000, of which \$241,000 would come from gravel and \$60,000 would come from sand.

Table 2. Estimated in-place, sterilized, and exploitable sand and gravel resources in esker deposits in the Soucook River valley part of the Loudon, N.H., 7.5-minute quadrangle.

[Sand and gravel in eskers 1, 5, and 6 previously have been removed. Values are rounded to three significant digits. st, short tons.]

Esker No.	In-Place Resources	Sterile Resources	Exploitable Resources	Exploitable Sand	Exploitable Gravel	Exploitable Sand	Exploitable Gravel	Exploitable Sand	Exploitable Gravel	Exploitable Total
	(m ³) [yd ³]	(st)	(st)	(\$)	(\$)	(\$)				
2	17,300 [22,600]	5,240 [6,850]	12,100 [15,800]	8,490 [11,100]	3,630 [4,750]	13,300	7,120	1,330	5,340	6,670
3	151,500 [198,000]	71,100 [93,000]	80,400 [105,000]	56,300 [73,600]	24,160 [31,500]	88,300	47,300	8,880	35,500	44,400
4	122,000 [160,000]	879 [1,150]	121,000 [158,000]	84,900 [111,000]	36,400 [47,600]	133,000	71,400	13,300	53,600	66,900
7	91,800 [120,000]	8,420 [10,800]	83,300 [109,000]	58,300 [76,300]	25,000 [32,700]	91,600	49,100	9,160	36,800	46,000
8	487,000 [637,000]	0 [0]	487,000 [637,000]	341,000 [446,000]	146,000 [191,000]	535,000	287,000	53,600	215,000	269,000
9	625,000 [817,000]	54,300 [71,000]	570,000 [746,000]	399,000 [522,000]	171,000 [224,000]	627,000	336,000	62,800	251,000	314,000
10	288,000 [377,000]	85,000 [111,000]	203,000 [301,000]	142,000 [186,000]	60,900 [79,700]	223,000	119,000	22,300	89,600	112,000
11	77,000 [101,000]	72,600 [95,000]	4,350 [5,690]	3,060 [4,000]	1,310 [1,710]	4,780	2,560	480	1,930	2,410
12	285,000 [373,000]	248,000 [324,000]	36,600 [47,900]	25,600 [33,500]	11,000 [14,400]	40,300	21,600	4,030	16,200	20,200
TOTAL	2,140,000 [2,800,000]	546,000 [714,000]	1,600,000 [2,090,000]	1,120,000 [1,460,000]	479,000 [627,000]	1,760,000	941,000	176,000	706,000	881,000

NON-ESKER DEPOSITS

Although eskers are extraordinary sources of gravel, there are other sites in the valley, such as glacial outwash deltas and stream terraces, that contain stratified glaciofluvial sand and gravel. A different approach, one more reliant on GIS, was necessary to estimate these resources, because these non-esker deposits are not as well defined topographically as the eskers. Clearly, the 20-ft contours on the topographic map could not be used to estimate the thickness and extent of stratified beds less than 5 to 10 ft thick.

Whenever a glacial stream flows into a standing body of water, such as a glacial lake, its velocity and transporting power are quickly stemmed and it drops its coarsest sediments. If conditions are favorable, a delta will form (fig. 3). This happens in an orderly pattern with sand being deposited in foreset beds, which are the steeply dipping strata forming the main body of the delta. Foreset beds are made chiefly of sand with minor amounts of gravel. Finer materi-

al (silt and clay) is swept further along and settles on the lake floor as lake-bottom sediments (bottomset beds). As the delta builds out into the lake, the glacial stream extends out over the delta and covers the foreset beds with topset beds. Topset beds contain the coarsest material in the delta and are a source of gravel. Figure 7 shows foreset and topset beds in a small glaciofluvial delta.

Stream terraces form when a valley choked with sediment is incised as a stream cuts its way down to a lower level. The stream cuts a channel down through old glaciofluvial deposits and creates a new flood plain. Remnants of the old flood plain may be left standing at the higher level, forming terraces on one or both sides of the stream. If the older glaciofluvial deposits consist of coarse sand and gravel, they may be a valuable resource. Careful interpretation of topographic contours may reveal the presence of stream terraces along streams in glaciofluvial terrains.

Estimating the sand and gravel resources in non-esker glaciofluvial deposits consists of several steps, each of which employ GIS. The digital geologic map is used to define the



Figure 7. Photograph showing a small glaciofluvial delta. Examples of gravel sizes in deltaic deposits are seen in the foreground.

area expected to contain glaciofluvial gravel resources (this was mostly the footprint of glacial Lake Hooksett). Much of the quadrangle was omitted because the glaciofluvial system was confined to the Soucook River valley floor.

Areas outside of the valley floor are mapped as till, which is unlikely to contain economic sand and gravel deposits. Till is unstratified drift deposited directly by the glacier with little or no modification by meltwater. The grain size ranges from clay to large boulders, but is mostly silt to pebble sized. Till is poorly sorted and may be loosely packed and sandy to compacted and silty. A high portion of till must be processed to obtain a large quantity of gravel, so mining till for sand and gravel usually is not economical.

ESTIMATE OF SAND AND GRAVEL RESOURCES

Once the area where glaciofluvial sand and gravel deposits were likely to occur in the valley was identified, a method was developed to estimate the sand and gravel resources within that area. The method involved creating digital lattices or grids representing the following surfaces in the study area: the topographic surface, the water table, and the base of the sand and gravel deposits. In addition, the percentage of gravel and sterilization also are expressed as surfaces.

TOPOGRAPHY

One of the most important surfaces is topography, because the differences in elevation are used to calculate the thicknesses of the stratified deposits. A digital elevation model (DEM) of the topography of the Loudon 7.5-minute quadrangle was obtained from the USGS Web site (http://edcftp.cr.usgs.gov/pub/data/DEM/7.5min/L/loudon_Nh/. Accessed February 1999.) and converted to a georefer-

enced lattice or matrix representing the three-dimensional topographic surface of the quadrangle. Each cell in the standard DEM lattice represents the elevation of one 30 m × 30 m cell in the quadrangle. The lattice was then resampled so that each cell was 10 m × 10 m; this smaller cell size was used to better fit the resolution for the 1:24,000 scale of the Loudon quadrangle and to follow more closely the 50-ft and 75-ft buffers along the roads and streams. Just as a standard topographic map might be used, the topographic surface was the base for further calculations to estimate the sand and gravel resources in the valley.

WATER TABLE

The water table is important to modern sand and gravel mining because environmental regulations mostly prohibit removal of material below the water table. This factor greatly reduces the amount of sand and gravel resources available for mining and must be accounted for in any resource estimate. Many of the water-well completion reports (New Hampshire Department of Environmental Services, written commun., February 1998) listed the static water level of the well. From this information, the elevation of the water table was calculated; with numerous wells, the surface of the water table was easily calculated for the entire river valley within the Loudon quadrangle.

Data acquired from the water-well completion reports included the following:

1. Elevation of the drill site—The basic reference from which other depths and thicknesses were calculated;
2. Static water level—The depth to the top of the water table;
3. Geologic formation description—May be used as

- an approximation for gravel grade;
4. Thickness of formation penetrated;
 5. Location—Given as precise latitude and longitude or estimated from an accompanying map; and
 6. Depth to bedrock—A limiting factor for the thickness of the stratified deposits.

A digital surface model of the water table was developed by subtracting the static water-level elevations from the water-well collar elevation at each well site. Wells in the Soucook River valley, however, are scattered and limited in number; therefore, they did not yield a representative surface and had to be augmented by information from the topographic map. Streams and lakes represent places where the water table is at the surface, so the surface elevations of the streams or lakes were considered equivalent to the static water level. Therefore, wherever a stream crossed one of the 20-ft contours on the map in the Soucook River valley part of the quadrangle and at each body of standing water, a water-table data point was generated as an elevation.

A spline function, based on data from the wells, streams, and lakes, was used to calculate the elevation of the water table at any location in the Soucook River valley part of the quadrangle where sand and gravel resources are expected. A spline is a two-dimensional minimum curvature interpolation resulting in a smooth (continuous) surface that passes exactly through the input points. The basic minimum-curvature technique is also referred to as thin-plate interpolation. Figure 8 shows 2-m contours of the water-table surface. Adjustments were made to the stream data in some sites so that the surface of the calculated water table remained beneath the topographic surface.

BASE OF SAND AND GRAVEL DEPOSITS

The base of the sand and gravel deposits that formed in the glacial lake represents an important datum because the difference between it and the topographic surface is the thickness of the sand and gravel deposits. The elevation of the base of the sand and gravel deposits was calculated using the descriptions of the stratified units penetrated by water wells and their depths. Data points also were added from the geologic map where the sand and gravel deposits were known to thin to zero. The spline function was used again to create a lattice representing the three-dimensional surface of the base of the sand and gravel beds. Data adjustments were made when the calculated base of the stratified deposits was above the topographic surface, inferring a negative thickness to the deposits. Figure 9 is a map showing the thickness of the sand and gravel deposits in the Soucook River valley.

PERCENT GRAVEL

A surface representing the percentage of gravel underlying any location in the river valley was developed for use in estimating the total sand and gravel resources. This is because the glaciofluvial deposits vary greatly in the percentage of the prized gravel that is contained versus the percentage of the less-valued sand. The percentage of gravel for each 10 m × 10 m cell was multiplied by the estimated thickness of that cell to determine the sand and gravel resources. The totals for individual cells were added together to yield the total percentage for the Soucook River valley. The percentage of gravel in the glaciofluvial deposits was estimated from two sources—the geologic map of the quadrangle and the water-well completion reports.

The geologic map of the Loudon quadrangle classifies stratified deposits as belonging to one of four textural categories (estimated to a depth of at least 5 ft): (1) cobble and boulder gravel, (2) cobble and pebble gravel and sand, (3) sand with minor pebble gravel, and (4) silt and clay. Each of these categories was assigned a gravel percentage based on its description. Cobble and boulder gravel contains about 30 percent gravel and 70 percent sand. These are high-energy, poorly sorted, and poorly stratified deposits where fine sand, silt, and clay were carried off by moving water, leaving behind cobble and boulder gravel with coarse interstitial sand. The non-esker deposits of this class make up 347,000 m² (about 1.7 percent) of the Soucook River valley in the quadrangle. The total area of the Soucook River valley in the Loudon quadrangle is about 20,400,000 m². The cobble and pebble gravel and sand category contains about 25 percent gravel and 75 percent sand; these sediments represent topset beds proximal to the retreating ice sheet, lake-edge sediments, and stream terraces. This category makes up 5,440,000 m² (almost 27 percent) of the sediments of this part of the Soucook River valley. Sand with minor pebble gravel contains 10 percent gravel and 90 percent sand—a marginal to subeconomic resource at best. Topset and foreset beds more distal to the stagnant ice sheet and some proximal lake-bottom sediments consist of sand with minor pebble gravel. Sand with minor pebble gravel deposits makes up 9,170,000 m² (almost 45 percent) of the sediments of this part of the valley. The silt and clay class contains no gravel resources and represents lake-bottom sediments. The geologic map shows only one place, an area of 20,000 m² (slightly less than 0.1 percent), in the river valley where silt is at the surface. Silt and clay deposits reported in the water-well completion reports were not included in sand and gravel resource calculations. About 19.1 percent of the river valley consists of gravel pits, artificial fill, swamps and marshes, and other areas without stratified deposits.

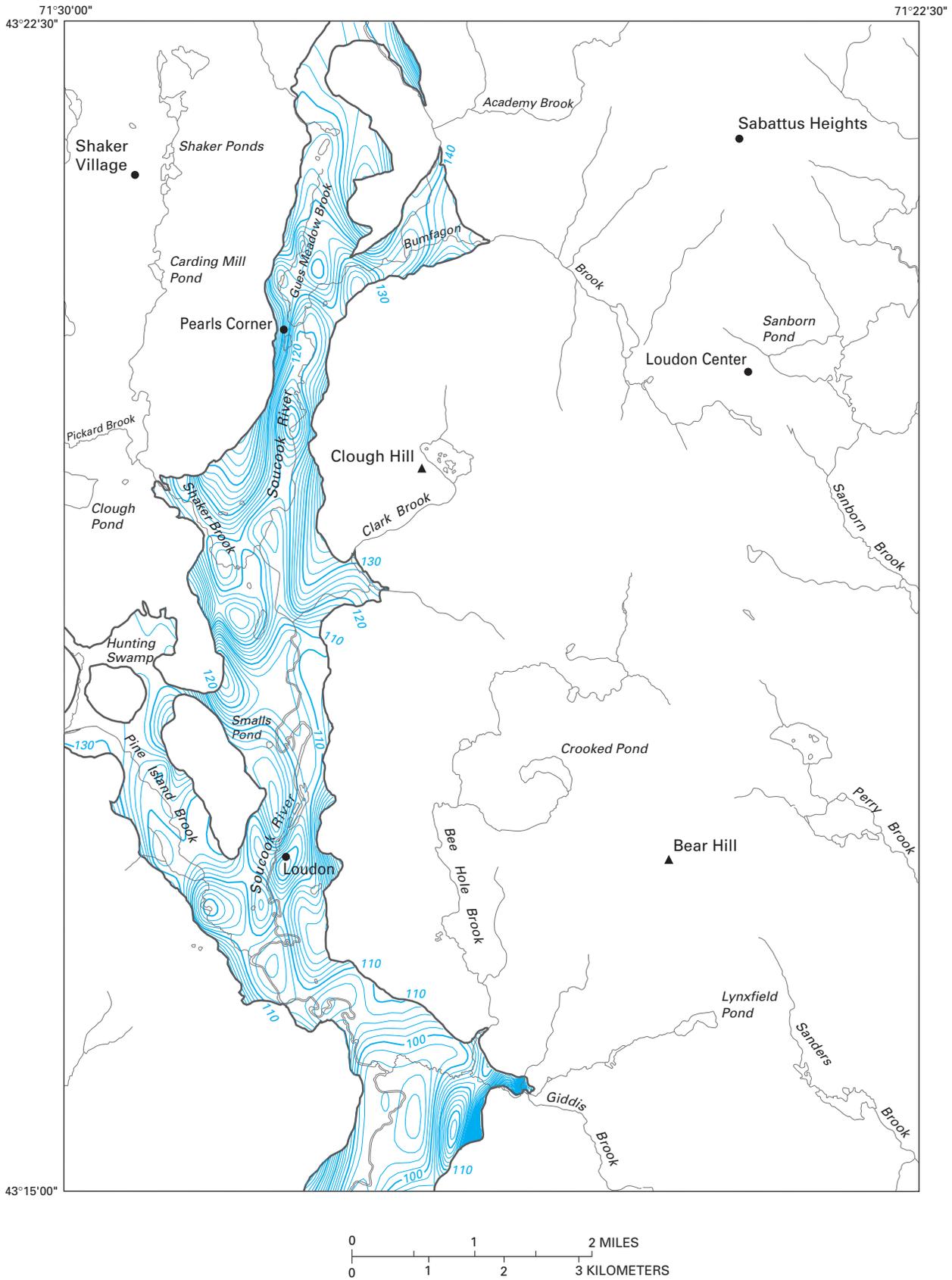


Figure 8. Map showing the water table of the Soucook River valley in the Loudon, N.H., quadrangle. The contours represent 2 m of elevation.

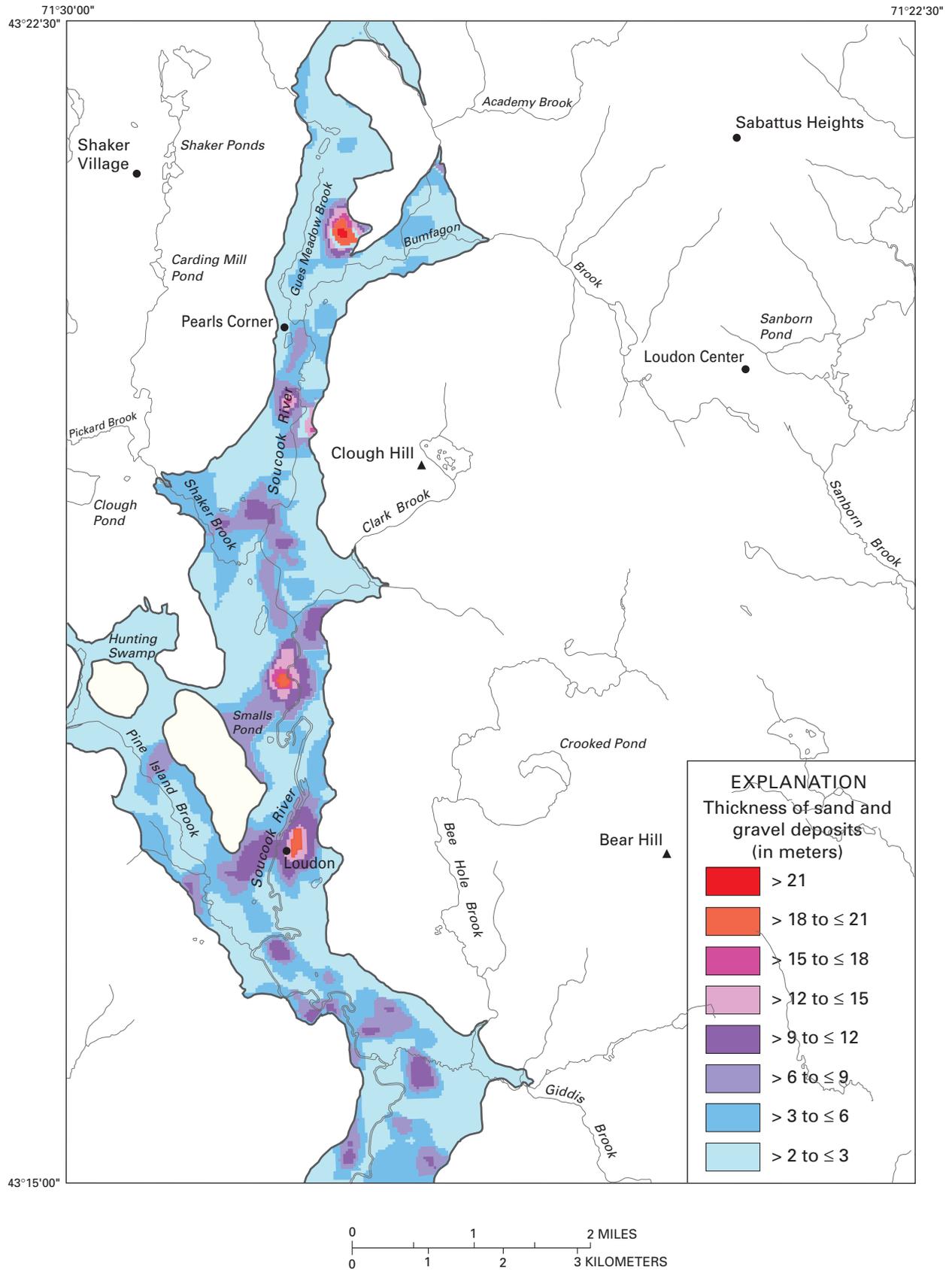


Figure 9. Map showing thickness of the sand and gravel deposits of the Soucook River valley in the Loudon, N.H., quadrangle.

At the edges of the deposits, the percent gravel was set to zero. The spline function again was used to create a surface between data points. Figure 10 is a map of the gravel grades in the Soucook River valley.

STERILIZATION

The sterilization lattice consists of the streams and roads and their respective 50- and 75-ft buffers, present and abandoned gravel pits, and the locations on the urbanization map where mining is unlikely to occur (fig. 11). These areas were made into a mask to overlay the other lattices, so that only nonsterilized sand and gravel deposits were counted as resources. Figure 12 shows the nonsterilized areas of the valley superimposed on the map of the thickness of the sand and gravel deposits.

A hypothetical cross section of the Soucook River valley in the Loudon quadrangle (fig. 13) shows the relative positions of the topography, water table, and bottom of the gravel deposits. Shown also are the sterilized areas where the gravel resources are not available for exploitation. In this example, a large part of the resources cannot be mined, because they are beneath the water table; are in the proximity of roads, streams, or private housing; or they have been removed by previous mining.

ANALYSIS

The sand and gravel resources of the non-esker stratified deposits in the Soucook River valley were estimated using surfaces representing the topography, water table, base of the sand and gravel deposits, percent gravel, and sterilization described above. The elevation of each of the cells in the surface representing the base of the sand and gravel deposits was subtracted from the topographic surface. This resulted in the estimated thickness of the sand and gravel deposits everywhere on that surface (fig. 10). The volume of sand and gravel in each cell of a lattice is the area of the cell multiplied by the thickness. The 100-m² area of each 10 m × 10 m cell was multiplied by the thickness to yield the volume of sand and gravel resources. The sum of the volumes of the cells in the lattice yields the total volume of sand and gravel in the valley. In this instance, the total volume of the stratified deposits is estimated to be 158,000,000 m³ (206,000,000 yd³). This is the endowment, or the maximum amount, of sand and gravel (including the eskers) that could be exploited if there was no sterilization by environmental or urban restrictions, regardless of economics, and the river valley was stripped bare.

Restrictions on mining reduce the volume of sand and gravel resources that can be exploited. One of the restric-

tions is that mining of sand and gravel cannot take place below the water table. To estimate the amount of resources that may be exploited without going beneath the water table, the elevation of the water table in each cell must become part of the equation. As illustrated in figure 13, the thickness of the stratified deposits above the water table is the thickness of the stratified deposit minus the part that is below the water table. Using GIS software, the volume of this material below the water table was subtracted from the total volume of the sand and gravel endowment. The total volume of sand and gravel in these deposits above the water table is 64,500,000 m³ (84,400,000 yd³), leaving about 94,000,000 m³ (123,000,000 yd³) (59 percent) of the total endowment of 158,000,000 m³ (206,000,000 yd³) of sand and gravel below the water table and unavailable for mining.

The map of the thickness of the stratified deposits above the water table (fig. 12) shows that the thickest deposits generally follow the course of the Soucook River. The thickness, however, varies markedly over the length of the river. The presence of eskers, which are topographic highs, undoubtedly accounts for some of the thickness of the deposits in the northern part of the quadrangle. In the central part of the Soucook River valley in the Loudon quadrangle, the modern river follows the path set by the eskers; eskers are located on one side or another for much of its course (fig. 5). In some places, the sand and gravel deposits are more than 72 ft thick; in other places, they are as thin as 2 ft. At the edge of the Soucook River valley, the thickness of the stratified glaciofluvial deposits goes abruptly to zero as the deposits did not form beyond this environment. The mean thickness of the nonsterilized deposits over the river valley is about 11 ft, but in much of the valley the deposits are much thinner.

The village of Loudon, N.H., overlies a major part of one of the largest areas of thick sand and gravel deposits, thus sterilizing them. Several of the gravel pits occur where the map suggests that the sand and gravel deposits above the water table are rather thin. These may be sites where thin topset beds or stream terraces of high-grade gravel were mined.

The contribution of the non-esker sand and gravel beds above the water table is quite variable. Beds 12 to 16 ft thick contribute the greatest part of the resources (almost 13 percent) (table 3). Beds 4 to 28 ft thick account for 58 percent of the area and for more than 65 percent of the resources, while beds 8 ft or thinner account for more than 51 percent of the area but a mere 17 percent of the resources.

Table 4 shows the results of analyzing the relationship of the digital surfaces in the GIS. The amount of unsterilized sand and gravel deposits above the water table is 46,100,000 m³ (60,300,000 yd³). Of this material, 8,950,000 m³ (11,700,000 yd³) (more than 19 percent) is gravel and 37,200,000 m³ (48,700,000 yd³) (81 percent) is sand. Adding the 1,600,000 m³ (2,090,000 yd³) of nonsterile material in the esker deposits (tables 2 and 4) brings the total nonsterile resources above the water table to 47,700,000 m³

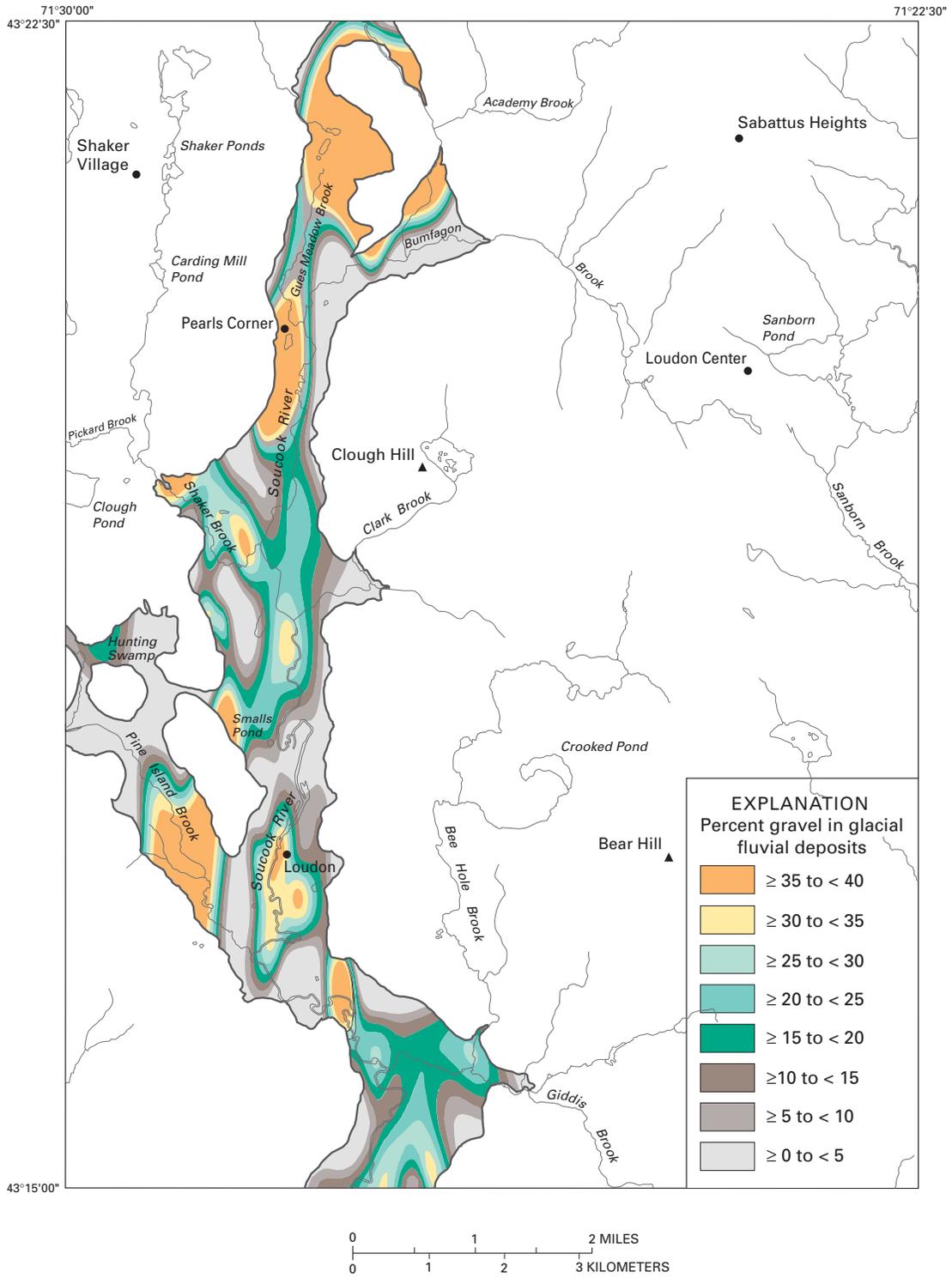


Figure 10. Map showing the percentage of gravel in glaciofluvial deposits of the Soucook River valley in the Loudon, N.H., quadrangle. Percentage of gravel may be as much as 40 percent.

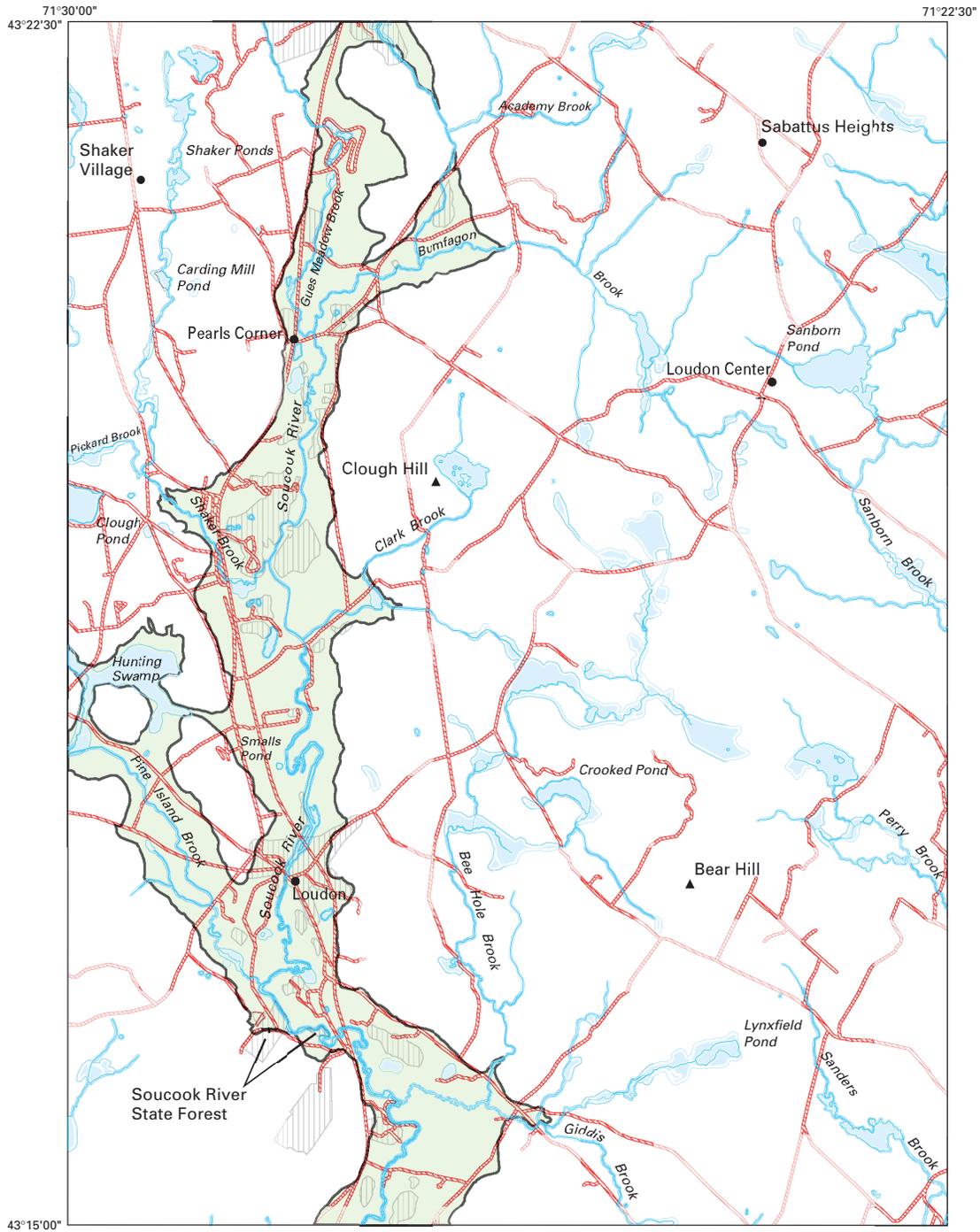


Figure 11. Map showing areas of the Soucook River valley part of the Loudon, N.H., quadrangle that have been sterilized because of the presence of roads, streams, and urbanization.

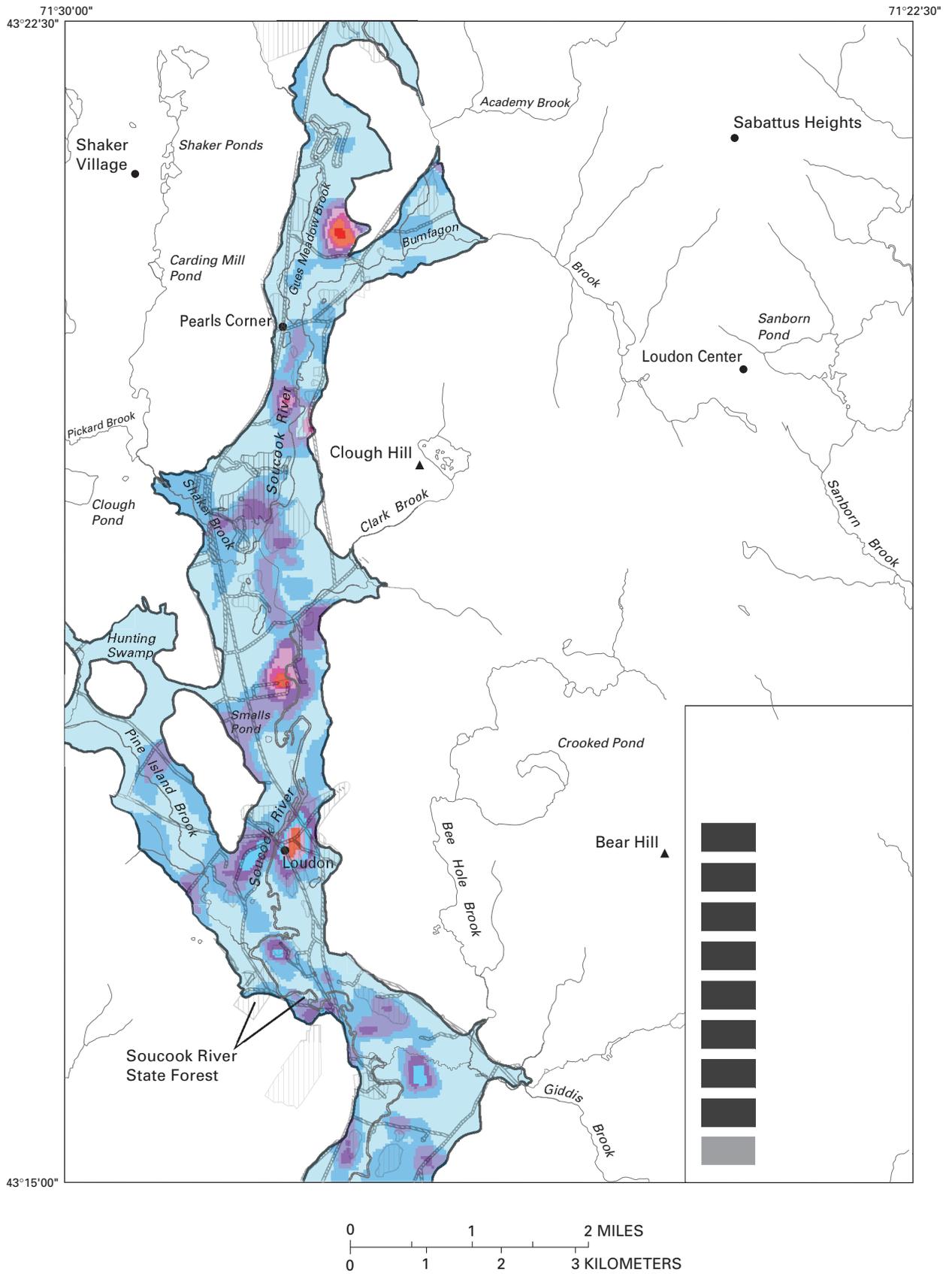


Figure 12. Map showing thickness of the sand and gravel deposits in the Soucook River valley part of the Loudon, N.H., quadrangle, and areas that have been sterilized.

Table 3. Contributions to total non-esker resources of sand and gravel deposits in the Soucook River valley
[Resources in sterilized areas are not included. Values are rounded to three significant digits.]

Deposit thickness (ft)	Area (m ²)	Percent of total area	Volume (m ³)	Volume (yd ³)	Percent of total volume
0 to <4	4,530,000	33.75	3,760,000	4,920,000	8.14
4 to <8	2,370,000	17.66	4,260,000	5,570,000	9.23
8 to <12	1,840,000	13.70	5,560,000	7,270,000	12.05
12 to <16	1,410,000	10.50	5,980,000	7,820,000	12.97
16 to <20	1,000,000	7.48	5,460,000	7,140,000	11.84
20 to <24	677,000	5.04	4,510,000	5,900,000	9.78
24 to <28	537,000	4.00	4,250,000	5,560,000	9.20
28 to <32	116,000	0.86	3,520,000	4,600,000	7.62
32 to <36	466,000	3.47	2,000,000	2,610,000	4.34
36 to <40	112,000	0.84	1,300,000	1,700,000	2.82
40 to <44	130,000	0.96	1,660,000	2,170,000	3.60
44 to <48	67,500	0.50	937,000	1,230,000	2.03
48 to <52	44,100	0.33	667,000	872,000	1.45
52 to <56	30,600	0.23	504,000	659,000	1.09
56 to <60	33,300	0.25	589,000	770,000	1.28
60 to <64	21,600	0.16	406,000	531,000	0.88
64 to <68	19,800	0.15	395,000	517,000	0.86
68 to <72	13,500	0.10	288,000	377,000	0.62
72 and greater	3,600	0.03	78,700	103,000	0.17
TOTAL	13,400,000	100.00	46,100,000	60,300,000	100.00

Table 4. Estimated sand and gravel resources in non-esker deposits and total resources above the water table in the Soucook River valley.
[Values are rounded to three significant digits. st, short tons.]

Category	Total Resource (m ³) [yd ³]	Sand (m ³) [yd ³]	Gravel (m ³) [yd ³]	Sand (st)	Gravel (st)	Sand (\$)	Gravel (\$)	Total (\$)
Part 1 totals: Nonsterile sand and gravel in eskers	1,600,000 [2,090,000]	1,120,000 [1,460,000]	479,000 [627,000]	1,760,000	941,000	176,000	706,000	881,000
Part 2 totals: Nonsterile sand and gravel above the water table	46,100,000 [60,300,000]	37,200,000 [48,700,000]	8,950,000 [11,700,000]	58,400,000	17,600,000	5,840,000	13,200,000	19,000,000
Parts 1 and 2 totals:	47,700,000 [62,400,000]	38,300,000 [50,100,000]	9,400,000 [12,300,000]	60,100,000	18,500,000	6,010,000	13,900,000	19,900,000
Total sand and gravel above the water table including all the eskers	64,500,000 [84,400,000]	51,800,000 [67,800,000]	12,800,000 [16,700,000]	81,300,000	25,000,000	8,130,000	18,700,000	26,900,000
Total estimated sand and gravel endowment	158,000,000 [206,000,000]							

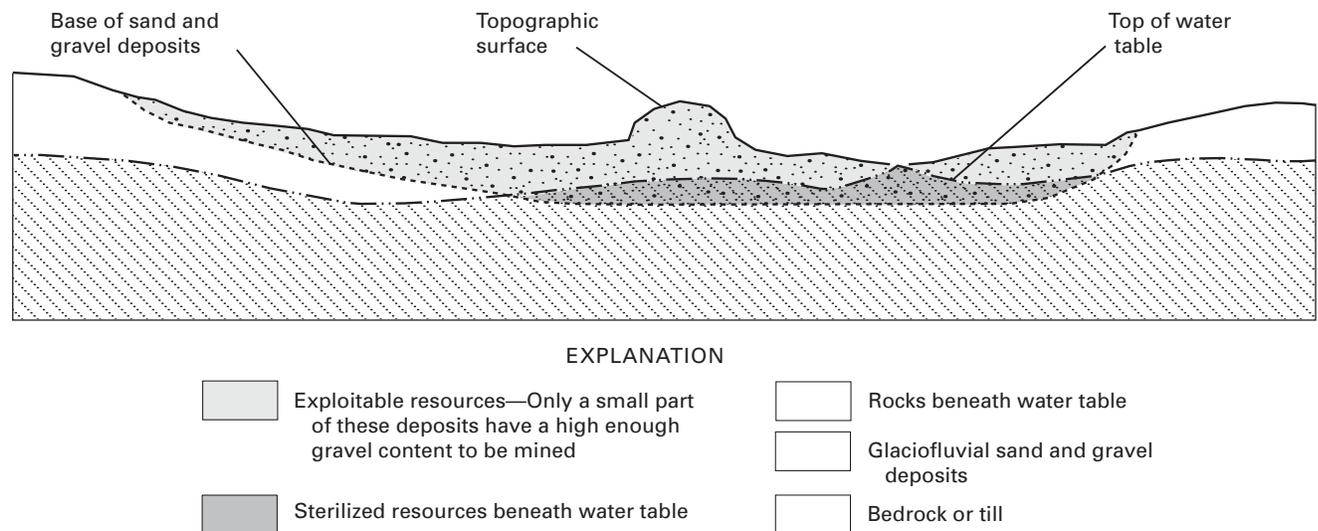


Figure 13. Hypothetical cross section of the Soucook River valley in the Loudon, N.H., quadrangle showing the relative positions of the topography, water table, base of the sand and gravel deposits, areas having gravel resources, sterilized areas, and exploitable areas.

(62,400,000 yd³) of sand and gravel. Of the latter resources, more than 80 percent is sand and almost 20 percent is gravel. The 1,600,000 m³ (2,100,000 yd³) of nonsterile sand and gravel resources in the esker deposits amounts to less than 4 percent of the total nonsterile sand and gravel resources in the Soucook River valley part of the quadrangle.

When the sand and gravel tonnages are converted to gross in-place dollar values, a measure of the relative wholesale value of these resources is evident. The non-esker resources contain a total value of \$19,000,000, of which over \$13,200,000 are gravel resources and \$5,840,000 are sand resources. Adding the values estimated for the eskers brings the total nonsterilized sand and gravel resources for the valley to almost \$19,900,000 of which about \$13,900,000 (about 70 percent) are gravel resources and almost \$6,010,000 (more than 30 percent) are sand resources. These estimated wholesale values are for comparison only and do not take into account economic factors which influence whether a deposit ever goes into production.

CONCLUSIONS

The 12 known eskers in the valley cover a total of 370,000 m². About 264,000 m² of these eskers occur outside buffer areas for streams, roads, or urbanization. The eskers in the Loudon quadrangle are about 2.8 times larger in volume than those modeled by Bliss (1998). Approximately 1,600,000 m³ (2,090,000 yd³) of sand and gravel resources in the eskers remain available for possible exploitation. The total gross in-place value of the nonsterilized esker sand and gravel resources at wholesale prices is \$881,000, of which \$706,000 is gravel and \$176,000 is sand.

The estimate of sand and gravel resources in non-esker deposits used an approach reliant on GIS. The geologic map was used to define the area expected to contain gravel resources and to omit areas where gravel deposits are unlikely to occur. The percentage of gravel in various parts of the valley was estimated from the geologic map and from water-well completion reports. Water-well completion reports also were a source of information on the thickness of the sand and gravel deposits, and the elevation of the water table.

The amount of nonsterile sand and gravel in non-esker deposits above the water table is 46,100,000 m³ (60,300,000 yd³). Adding the 1,600,000 m³ (2,100,000 yd³) of nonsterile material in the esker deposits brings the total nonsterile resources above the water table to 47,700,000 m³ (62,400,000 yd³) of sand and gravel, with more than 80 percent as sand and almost 20 percent as gravel. Esker deposits amount to less than 4 percent of the total nonsterile sand and gravel resources in the river valley and only a little more than 5 percent of the gravel resources.

Non-esker resources contain a gross in-place value of \$19,000,000 at wholesale prices, of which over \$13,200,000 is gravel and \$5,840,000 is sand. Adding the eskers brings the total nonsterilized sand and gravel resources for the valley to almost \$19,900,000, of which about 70 percent is gravel and over 30 percent is sand. These estimated wholesale values are for comparison only and do not take into account economic factors that influence whether a deposit ever goes into production.

The combination of geologic mapping, water-well data, topography, and other data in a GIS can be used to improve resource estimates of gravel and sand fractions. The basic methodology is transferable to any glaciofluvial environment, and the information gives local and regional planners a tool to optimize use of local sand and gravel resources.

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